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RECHERCHE

A SYSTEMATIC REVIEW OF THE ENERGY AND CLIMATE IMPACTS OF TELEWORKING

This review assesses how changes in working practices are associated with different forms of teleworking, including the use of different ICTs, various commuting/travel options, and different working spaces such as offices, cafes, libraries, and homes.

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A systematic review of the energy and climate impacts of teleworking

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Abstract:

Information and communication technologies (ICTs) increasingly enable employees to work from home and other locations (“teleworking”). This study explores the extent to which teleworking reduces the need to travel to work and the consequent impacts on economy-wide energy consumption, with clear implications for climate, energy, and environmental policy.

Methods/Design: This review assesses how changes in working practices are associated with different forms of teleworking, including the use of different ICTs, various commuting/travel options, and different working spaces such as offices, cafes, libraries, and homes. To do so, it conducts a systematic review of more than 9,000 published articles.

Review results/Synthesis: Overall, the review finds that 26 out of 39 relevant studies indicate that teleworking causes a reduction in energy use, and only eight studies indicate that teleworking leads to an increase (or only a neutral impact) on energy use. The main source of energy savings is via the substitution effect whereby teleworking leads to lower average vehicle distance travelled by those who telework either part of the week. The studies estimated that potential reductions in energy consumption as a result of reduced commuting travel could be as high as 20%. Other studies suggest possible energy savings through lower office energy consumption.

Discussion: Despite the generally positive verdict on teleworking as an energy-saving practice, analysis reveals that there are numerous uncertainties and ambiguities about the actual or potential benefits of teleworking. These relate to questions about exactly what proportion of workers or frequency of teleworking is needed to bring a net reduction in energy use through avoided work travel. They also relate to questions about the extent to which teleworking may lead to unpredictable increases in non-work travel and home energy consumption that end up outweighing any gains from reduced work travel.

Keywords: systematic review; teleworking; telecommuting; digital economy; energy; climate change.

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1. Introduction

Efforts to reduce greenhouse gas (GHG) emissions focus upon both technological innovation and behavioural change, while recognizing that these domains are interdependent (Bel et al. 2018; Creutzig et al. 2018; Dubois et al. 2019). One area that has received particular attention is encouraging technology-enabled changes in working patterns to commuter travel and office-related energy consumption (Hopkins & McKay 2018). Since the transport sector in the United States (US), for example, accounts for around 33% of final energy use, a reduction in work-transport could have a significant impact (Zhu & Mason 2018).

One trend that could reduce energy consumption and thus carbon emissions from travel is teleworking¹, where employees use information and communication technologies (ICTs) to work from home, in satellite telecentres or in other locations. Employees may telework part-time or, less commonly, full-time (Hynes 2016; Giovanis 2018). However, despite assumptions that teleworking would provide an important contribution to a ‘lower energy future’, evidence of its impacts is inconclusive (Brand et al. 2019). Indeed, while some studies suggest that teleworking can reduce energy consumption (primarily through avoided commuting) by as much as 77% (e.g. Koenig et al. 1996), others find much smaller gains, with some studies suggesting a paradoxical *increase* in energy consumption (e.g. Rietveld 2011).

This lack of consensus on the environmental benefits of teleworking has arguably contributed to the lack of coordinated promotion of teleworking by business or government, even in countries where multiple studies have been conducted – such as the US (Allen et al. 2015). Indeed, despite the promise of energy savings and other social benefits, teleworking has not grown as rapidly as predicted, even in sectors and regions that appear well-suited to it – such as growing cities in developing countries (Ansong & Boateng 2018). For example, Zhu (2018) estimates that only around 9% of the US working population teleworks more than once a week.

This uncertainty about environmental benefits is compounded by persistent scepticism about the social implications of teleworking. Many believe, for example, that practices such as ‘face to face’ meetings’ are essential for building confidence between colleagues and clients and cannot be substituted by ‘virtual meetings’ enabled by ICT (Baruch 2001). Other studies have suggested that concerns about emotional isolation or future career advancement may hinder people’s willingness to adopt teleworking (Golden et al. 2008; Schulte 2015). For firms, concerns over accountability and productivity persist, despite evidence to the contrary (Pérez et al. 2005).

In this context, this paper provides a systematic review of the current state of knowledge about the energy impacts of teleworking. This includes the energy savings from reduced commuter travel and the indirect impacts on energy consumption associated with changes in: a) non-work travel by both the teleworker and other household members; b) the size and occupancy of work premises; and c) the location and occupancy of employees’ homes. The aim is to identify the conditions under which teleworking can lead to a net reduction in overall energy consumption, and the circumstances where the benefits from teleworking are outweighed by the unintended impacts, such as greater private travel or increased non-work energy consumption. The latter are commonly referred to as ‘rebound effects’ (Berkout & Hertin 204; Horner et al. 2016).

¹ Within the literature on home- or office-based working as a travel or environmental policy, a number of different terms are used. ‘Teleworking’ and ‘telecommuting’ are the most popular, but a host of others are also used, such as ‘remote working’, and ‘flexible working’. For the purposes of this study, ‘teleworking’ will be used.

Our interest is the impacts of teleworking on economy-wide energy consumption, taking into account the full range of mechanisms through which those impacts occur. But many studies have a narrower *scope*, in that they focus upon a more limited range of impacts, such as the changes in commuter travel alone. These studies may nevertheless provide useful evidence, as they frequently capture the most *important* impacts. Similarly, many studies use different *metrics* to measure those impacts, such as changes in vehicle distance travelled. Again, these studies may provide useful evidence, as there is frequently an approximately linear relationship between those metrics and energy consumption. However, it is important to recognise that studies with a narrower scope will omit many important categories of impact, and studies with a different metric will provide rather inaccurate measures of the impact on energy consumption.

The article is structured as follows. Section 2 summarises the academic and policy debates about the energy and environmental benefits of teleworking. Section 3 outlines the systematic review methodology, while Section 4 presents the key results of the 39 identified studies. Section 5 discusses these results in more detail, including the magnitude of the identified impacts, the determinants of those impacts, and the source and scale of associated rebound effects. It also assesses the scope of the studies in terms of the types of impact that are included, as well as their methodological quality. Section 6 summarises the overall findings and reflects upon their implications for research and policy.

2. Teleworking and the impacts on energy use and emissions

‘Teleworking’ means working either full- or part-time from home, from a ‘telecentre’ located close to home, or from other locations. The practice has grown in popularity as technology has improved, but definitional ambiguities and data limitations make it difficult to estimate the precise number of teleworkers at any one time (Mokhtarian et al. 2005). The concept of teleworking can be traced back to the 1960s when ICTs such as telephones and fax machines were first mooted as offering the possibility of liberating workers from commuting to work every day (Mokhtarian 1997). At this time, however, teleworking was largely promoted as a *social* policy that would enable workers to spend more time with their families and less time travelling (Johnson 2003).

The advent of the internet in the mid-1990s and innovations such as teleconferencing coincided with a focus on the broader benefits of teleworking and a shifting rationale for its expansion (e.g. Marvin 1997; Allenby & Richards 1999). The increasing prominence of climate change within popular discourse led teleworking to be seen as an *environmental* or *energy* strategy that could reduce air pollution related to peak-time traffic congestion (Niles 1994), along with energy use and emissions from travel to work (Henderson et al. 1996) and energy consumption within workplaces (Matthews & Williams 2005). The main source of these benefits was that working from home (or from satellite telecentres that were closer to the home than the workplace) should reduce the energy expended in both travelling to work (typically by private car) and in heating, cooling and lighting large office spaces (Marcus 1995; Williams 2003).

Appraising whether such changes in working practices have indeed had these benefits is difficult, however, since the enabling technology (ICTs) triggers a range of ‘direct’ and ‘higher-order’ effects that are very hard to measure. Frequently, these effects are both unexpected and unintended (Pohl et al. 2019). ‘Direct’ effects relate to the energy used in the manufacture, operation and disposal of ICTs together with the associated network infrastructure, while ‘higher-order’ effects relate to the changes in energy consumption stimulated by ICTs, including changes in individual behaviour (e.g. commuting behaviour) and changes in prices, consumption, investment and other variables throughout the economy (Horner et al. 2016). These higher-order effects take a number of forms that (both individually and collectively) may either increase or reduce energy consumption relative to a baseline

scenario where those changes do not occur. Table 1 provides a classification of these different types of impact, and illustrates this with examples relevant to teleworking.

Table 1. Classifying the mechanisms influencing the impact of ICTs on energy consumption

Pohl et al. (2019) aggregate categories	Horner et al. (2016) aggregate categories	Impact mechanism (+ or - impact on energy consumption)	Teleworking example	
Direct impacts	Technology perspective	Direct	Embodied energy (+)	Energy used to manufacture the ICTs and associated infrastructure needed to support teleworking
			Operational energy (+)	Energy used to operate the ICT equipment for teleworking, including cloud storage and video streaming
			Disposal energy (+)	Energy used to dispose of the ICT equipment for teleworking
Higher-order impacts	User perspective	Indirect: single-service	Efficiency/Optimisation (-)	(Does not apply in this example)
			Substitution (+ or -)	Energy saved by avoiding commuting to the office
		Indirect: complementary services	Direct rebound (+)	Energy consumed in longer commuting trips, owing to the availability of teleworking encouraging people to take jobs that are further away from home
	System perspective		Indirect rebound (+ or -)	Energy used for heating the home during days in which the commuter is working from home
		Indirect: economy-wide	Economy-wide rebound (+ or -)	Energy used and saved in multiple markets owing to economy-wide adjustments in prices and quantities (e.g., investments previously made in the car industry are now redirected towards ICTs).
	Indirect: society-wide	Transformational change (+ or -)	Energy used and saved because of far-reaching changes in the spatial structure of societies, including where people live and work.	

Source: Adapted by authors from Horner et al. (2016) and Pohl et al. (2019).

Note: In the case of teleworking, the substitution effect is normally considered to be the most significant.

Whether the economic and behavioural changes stimulated by teleworking lead to an overall reduction in energy consumption therefore depends upon the sign and magnitude of these different categories of impact – the relative importance of which is likely to vary with context and change over time (De Graff 2004; Horner et al. 2016). Since personal transport is significantly more energy intensive than ICT services, most studies of teleworking *ignore* the direct impacts altogether and focus solely upon the indirect impacts – and particularly those from reduced commuter travel (Horner et al. 2016). However, factors such as the short lifetime and rapid replacement of ICTs, their increasingly complex supply chains (including dependence on a growing range of rare earth elements), and the advent of cloud storage and video streaming (which are relatively energy intensive) may be contributing to a growing energy footprint for ICTs. Hence, these direct impacts may become a more significant focus of teleworking studies in the future (Chapman 2007; LaChapelle et al. 2018).

The focus of the majority of studies has been the nature and magnitude of the ‘higher-order’ impacts indicated in Table 1 (Horner et al. 2016; Pohl et al. 2019). The most commonly cited benefit of teleworking is its ‘substitution’ effect, whereby commuter travel is substituted (or displaced) by less energy-intensive activities or behaviours that are enabled by ICTs (Salomon 1998). Historically, this has typically involved using ICTs to work from home or from a ‘telecentre’ located closer to the home than the workplace (Balepur et al. 1998). More recently, there has been a rapid growth in mobile working from cafes, trains and other Wi-Fi-enabled locations, but the energy implications of these emerging practices have yet to be fully studied. Whether these substitution effects lead to a net

reduction in energy consumption (at either the individual or societal level) depends, however, on the higher-order impacts (Mokhtarian 2009). Indeed, in some circumstances teleworking could encourage changes in behaviour that *increase* work and/or non-work travel, and thereby energy consumption (Pérez et al. 2004; Williams 2011; Zhu 2012).

In the case of work-travel, for example, the ability of teleworkers to live further away from their place of work could mean that the longer trips they make on non-teleworking days (where, as is the norm, they are only *part-week* teleworkers) wholly or partly outweigh the travel and energy savings they make on days that they work from home (Bailey & Kurland 2002). These impacts will also depend on the mode of transport they use to commute to work: in countries where public transport is a common mode of commuting, teleworking practices will have less impact on energy use than in countries (such as the US) where the private car is the dominant mode (Mokhtarian 2009; Van Lier 2014). The energy impacts will further depend upon the energy efficiency and level of occupancy of the relevant mode (e.g. one person in a Sport Utility Vehicle (SUV) versus several hundred in a crowded train), and the carbon impacts will additionally depend upon the carbon intensity of the relevant energy carriers (e.g. gasoline versus electricity).

In the case of non-work travel, there is evidence that gaining more time at home as a result of teleworking may induce extra trips by teleworkers – for leisure and social purposes, for example – that would not have been made had the teleworker been commuting to work every day (Lyons et al. 2008). It may also enable greater use of the household car by other household members on days that the commuter works from home. This latter trend has been observed in countries where households have fewer cars, such as South Korea, where the car is more of a ‘scarce’ – and thus more desirable – commodity (Kim et al. 2015). Such examples of additional, non-work travel enabled by teleworking may be considered expressions of ‘latent’ travel demand (Mokhtarian et al. 1995).

Another induced travel effect could be where the feelings of isolation and sedentariness generated by teleworking stimulate a desire for movement and mobility (Gurstein 2002). This compensatory travel, which may involve habitual trips to libraries or cafes for work, may partly offset the travel and energy savings achieved by avoiding commuting (Rietveld 2011). Overall, these examples suggest that the travel demand displaced by teleworking may be partly offset by induced travel demand in other areas.

Home and office energy consumption is another area where the benefits of teleworking could potentially be offset (Pérez et al. 2004). For example, teleworking may lead to more energy being used at home (e.g. for heating, cooking and lighting) without any compensating reductions in the energy used at work (e.g. offices may continue to be heated and lit as much as before). There could be an ‘additive’ impact of teleworking if businesses neither move to smaller offices (which have a smaller energy footprint) nor close their offices in response to increased teleworking (Matthews 2003). The net result could be an increase in building energy consumption, and possibly total energy consumption, as a result of greater teleworking (Kitou & Horvath 2008)

At the societal level, the aggregation of these and other trends may generate broader indirect and economy-wide rebound effects (Horner et al. 2016). If households reduce car travel, they may spend the money they save on road fuel on other goods and services that also require energy and emissions to produce (Sorrell et al. 2019). Alternatively, if teleworking boosts labour productivity and stimulates economic growth, it could encourage increased consumption, travel and energy use by both producers and consumers (Lachapelle et al. 2018). Berkhout and Hertin (2004) draw attention to the potentially small impact of teleworking on energy consumption relative to other driving forces such as population and income growth. A summary of the direct and higher-order effects of teleworking at the individual and societal level is given in Table 2.

Table 2. Summary of direct and indirect impacts of teleworking on energy use and emissions

Type of effect	Nature of impact on energy use and emissions	
	<i>Reduce</i>	<i>Increase</i>
<i>Direct</i>		<ul style="list-style-type: none"> • Energy consumed in manufacturing, using and disposing of ICT equipment
<i>Higher-order</i>	<ul style="list-style-type: none"> • Reduction in commuting travel and energy use • Reduction in office energy use 	<ul style="list-style-type: none"> • Increase in weekly travel due to longer commute on non-teleworking days • Increase in non-work travel by teleworker • Increase in energy consumption at home for heating, cooling, lighting and other uses • Increase in travel by teleworking household due to increased availability of car

The identification of these higher-order effects suggests that, to accurately estimate the net energy impacts of teleworking, a study must have as broad a scope as possible: a narrow scope may mean that important impacts are overlooked (Berković et al. 2013). For example, a study may estimate the reduction in commuter travel from teleworking but ignore the increase in other forms of travel. Alternatively, a study may overestimate the energy savings from teleworking by assuming that all commuting is by car, thereby neglecting any commuting by public transport. Similarly, a study may estimate the energy savings from reduced commuting and reduced office use but ignore the increase in home energy use. A limited scope could therefore lead to either an over- or under-estimate of the energy savings from teleworking depending on the context-specific interactions between a range of variables (Mokhtarian 2009).

While the range of possible interactions among different variables suggests that studies should have a wide scope, there are considerable methodological challenges in designing studies that capture the full range of impacts from teleworking. As a result, most studies focus upon a narrower range of impacts, such as commuter travel alone, whose measurement is more feasible. As Horner et al. (2016, p. 14) observe, this is a more general problem when studying the impact of ICT on energy use:

The inability to draw concrete conclusions reflects, in large part, uncertainty regarding the rebound effect for ICT and the inability to disentangle root causes of interrelated economic effects. The dynamics of these effects are hugely dependent upon human behavior, which is laden with uncertainty and confounds efforts to achieve the full technical potential of ICT interventions.

3. Research design

3.1 Research questions and approach

Our primary research question is as follows:

- What are the determinants and magnitude of the impacts of teleworking on energy consumption or proxies for energy consumption such as distance travelled by car?

Our sub-questions were are follows:

- What are the full range of impacts identified in the literature?
- What are the key socio-technical determinants of those impacts?

To review the evidence on this topic, we employ the methodology of ‘systematic reviews’ (Petticrew & Roberts 2006). These offer a number of advantages over traditional literature reviews, including minimising unintentional bias (e.g. excessive self-citations, or citations of colleagues) and avoiding the exclusion of studies that are frequently overlooked (Haddaway et al. 2015). For these and other

reasons, many authors have called for greater use of systematic reviews in the area of energy and climate research (Sorrell 2007; Sovacool et al. 2018; Pereira and Slade 2019).

The first stage of our systematic review involved choosing search terms that were relevant to the selected topic. These were combined to construct search queries that were used in the search engines of two scholarly databases. The process was iterative, since small changes in the search terms can have a large influence on the number of identified sources. As such, while reviewing the bibliographies of review articles in the area (e.g. Horner et al. 2016), we repeatedly refined our search strings to ensure that they were capturing all of the identified studies.

The references generated by this search phase were then screened in order to remove irrelevant studies. This involved applying explicit inclusion and exclusion criteria to the title and abstract of the study, and if necessary, to the full text. Following this, information was extracted in a consistent way from each of the selected studies. Since the evidence was both quantitative and qualitative, as well as being highly variable and using a variety of metrics (e.g. energy use, distance travelled, carbon emissions), a narrative synthesis was considered most appropriate (Snilstveit et al. 2012). To formulate our search and screening protocols, we followed the guidelines of the Collaboration for Environmental Evidence (Haddaway et al. 2018) and used the free online platform CADIMA to perform the screening phase (Kohl et al. 2018).

3.3 Sources and databases

The evidence base includes peer-reviewed academic journals, conference proceedings, books, working papers, doctoral theses, and technical reports. We gave priority to studies that provided quantitative estimates, but also examined qualitative evidence to obtain a deeper understanding of the relevant mechanisms and determinants. Given the pace of technical change in this area, we considered that older studies were unlikely to be of much value. Hence, we confined the review to studies published after 1995, approximately the start of the ‘internet age’ (Huws 2013). We also confined the review to English language studies, since this was the language of the research team. We applied our search protocol to *Scopus* and *Web of Science*, which are the most widely used scientific literature databases. We also searched for relevant grey literature (technical reports, doctoral theses, working papers) through a combination of internet searches and checking the profiles of key researchers in the field and the bibliographies of the identified studies.

3.4 Search terms and combinations

We combined three types of keywords in our search query, namely: a synonym for ‘teleworking’; a second for ‘energy’ (including various proxies for energy such as distance travelled); and a third that referred to the relationship or interaction between these two. We investigated exhaustive variations around these terms using the Boolean OR operator, and combinations of them using the Boolean AND operator, and made sure that studies identified by other authors (e.g., Horner et al. (2016)) were caught. This led to an extensive search string for each database (see Supplementary Material 1).

3.5 Inclusion and exclusion criteria

The search results were merged, and duplicates removed to obtain our initial sample. We then applied the inclusion/exclusion criteria in Table 3 to select only those studies that appeared relevant to our research question. Analysis of this preliminary sample led to the exclusion of further studies in which results or data were duplicated or where, on closer inspection, relevant data were not present. Once the final set of studies had been defined, we extracted the data into an Excel file (see Supplementary Material 2). The key results are summarised in Section 4.

Table 3. Inclusion and exclusion criteria used to screen the identified studies.

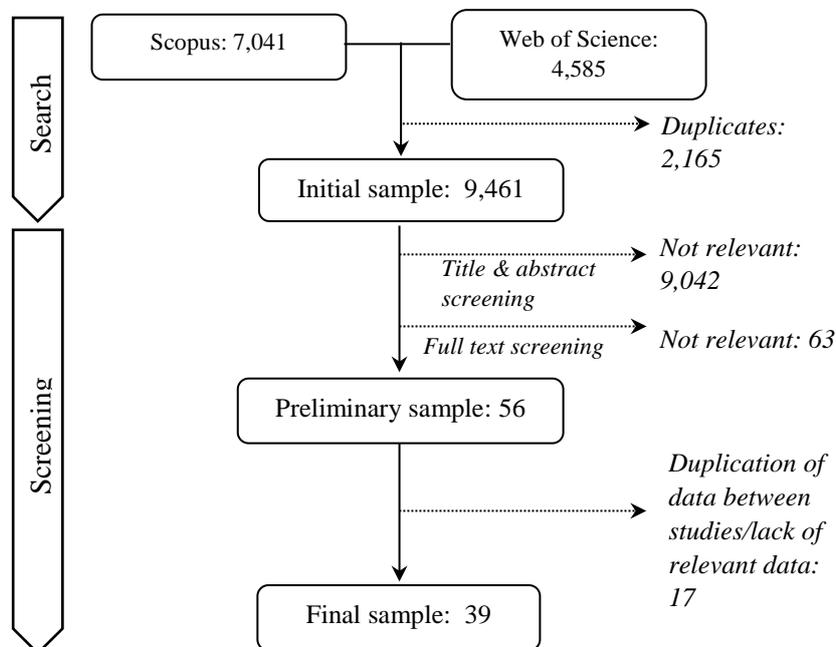
<i>Inclusion criteria (IC)</i>	
IC1	Refers to an analysis of ICT-enabled teleworking
IC2	Refers specifically to an energy-related effect of teleworking
IC3	Contains primary research results
<i>Exclusion criteria (EC)</i>	
EC1	The main topic does not relate to teleworking or energy
EC2	The study contains no quantitative analysis of the effects of teleworking on energy demand
EC3	The study is not accessible at the time of review (e.g. due to it being unpublished or behind a paywall)

4. Results: Searching, Screening and Data Extraction

4.1 Search and screening phases

As indicated in Figure 1, the search phase generated an initial sample of 7,041 references from *Scopus* and 4,585 from *Web of Science*, making a total of 11,626 references. This is a very large number compared to other systematic reviews because we were exhaustive when designing our search query. Adopting such a ‘large nest’ approach minimises the risk of missing relevant studies but leads to the inclusion of a large number of irrelevant studies that need to be screened out. After removing 2,165 duplicates, our initial sample comprised 9,461 references. Screening the titles and abstracts led to the removal of 9,042 irrelevant references, while full text screening led to the removal of an additional 63 studies. Our preliminary sample therefore consisted of only 56 studies, which was further reduced to 39 by removing studies with data that was duplicated in other studies or those which had no relevant primary data.

Figure 1. An overview of the literature search and screening phases



4.2 Data extraction

Table 4 summarises the extracted data from the 39 studies in our final sample, presenting the studies alphabetically (a more detailed table is provided in Supplementary Material 2). For each study, we include:

1. the study's number in the list;
2. the main author's name and the year of publication;
3. the country location;
4. the methodology (distinguishing between analysis of survey data, evaluation of pilot schemes, and scenario modelling)
5. the relevant metric (e.g. commuting distance travel);
6. the scope of the study (i.e. coverage of: i) commuter travel; ii) non-commuter travel; iii) home energy use; and iv) office energy use);
7. the estimated impact on the relevant metric ('increase', 'neutral', 'reduce', or 'unclear');
8. the nature and scale of that impact, including quantitative estimates; and
9. our appraisal of the methodological robustness of the study ('good', 'average', or 'poor')

Table 4. Key results from final study sample on teleworking and environmental impacts.

Study no.	Authors and date	Country	Methodology	Metrics	Scope (number of impact categories considered)	Impact on metrics	Nature/scale of impact	Methodological robustness
1	Asgari, H. & Jin, X. (2018)	USA	Analysis of survey data	Whether flexible commutes (part-day teleworking) enable reduced congestion.	1 (commuting travel only)	Unclear	Teleworking during peak travel times could potentially reduce peak travel (and thus congestion) by 20%.	Poor
2	Atkyns et al. (2002)	USA	Analysis of survey data	Vehicle distance travelled avoided by working from home.	1 (commuting travel only)	Reduce	Having one fifth of AT&T employees working one day a week from home could reduce vehicle distance travelled by 110,000 miles, reduce gasoline use by 5.1 million gallons, and reduce carbon emissions by 48,450 tons.	Average
3	Balepur et al. (1998)	USA	Evaluation of teleworking pilots	Vehicle distance and person distance avoided in working at telecentre vs. traveling to work/home-based telework	2 (commuting travel, non-commuting travel)	Reduce	A telecentre commuting frequency of one day a week led total weekly person travel to be reduced by 19% (17 miles) and weekly vehicle travel to be reduced by 19% (10 miles) compared with regular commuters who travel to the office every day.	Good
4	Bussière, Y. & Lewis, P. (2002)	Canada	Scenario modelling	Peak-time trips reduced through working from home.	1 (commuting travel only)	Reduce	Over 20 years (1996 to 2016) and assuming teleworking rates of 3.3% of the workforce in Montreal and 3.6% in Quebec, the number of peak-time trips would be reduced by 2.3% in Montreal and by 2.5% in Quebec.	Poor
5	Chakrabarti, S. (2018)	USA	Analysis of survey data	Annual miles driven per person	2 (commuting travel, non-commuting travel)	Increase	Frequent teleworkers travel 5.9% further by car each year than non-teleworkers and occasional teleworkers travel 8.0% further. This is because the longer commutes of teleworkers on days they work more than offset the savings made on teleworking days.	Good
6	Choo et al. (2005)	USA	Analysis of survey data	Vehicle distance travel avoided by working from home vs. traveling to work	1 (commuting travel only)	Reduce	Teleworking by 12% of the workforce once a week has reduced total annual vehicle miles travelled (VMT) in the US (estimated as 2.4 trillion miles) by 0.8%.	Good
7	De Abreu e Silva, J. & Melo, P. C. (2018)	UK	Analysis of survey data	Vehicle distance travel avoided by working from home vs. traveling to work for one and two-worker households	2 (commuting travel, non-commuting travel)	Increase	For single-worker households where the person teleworks once a week, there is an average increase of 9.7 miles travelled by all modes (9.0 by car, or 3.9%, 0.5 by public transport, or 2.4%, and 0.2 by non-motorized modes, or 3.8%). For two-worker households one day a week teleworking increases miles travelled by car by 1.6 miles (or 0.4%). This is lower than above because workers share trips.	Good
8	Dissanayake, D. & Morikawa, T. (2008)	Thailand	Scenario modelling	Vehicle distance travelled reduced and emissions avoided through the optimum placement of five satellite telecentres in the outer suburbs of Bangkok Metropolitan Region.	1 (commuting travel only)	Reduce	The modelled scenario for satellite telecentres reduces private vehicle usage in the area by 18–20%.	Poor
9	Ellder, E. (2017)	Sweden	Analysis of survey data	Whether teleworking reduces total travel distance.	2 (commuting travel, non-commuting travel)	Increase	Teleworkers travelled further than non-teleworkers on both teleworking and non-teleworking days. While non-teleworkers travelled an average of 46 km per day, teleworkers travelled 54km on teleworking days and 64km on non-teleworking days.	Good
10	Fu et al. (2012)	Ireland	Analysis of survey data	Energy used in commuting lifestyle vs home-working lifestyle	2 (commuting travel, home energy use)	Reduce	If 5% of the Irish population teleworked full time, final energy consumption would fall by 0.14%.	Good
11	Giovanis, E. (2018)	Switzerland	Analysis of survey data	Traffic volume and pollutants reduced	1 (commuting travel only)	Reduce	Teleworking by 8.43% of the population is associated with a reduction in traffic volume on average by 1.9% and equivalent reductions in various pollutants.	Average

12	Gubins et al. (2019)	Netherlands	Analysis of survey data	Commuting distance reduced by ICT-enabled home-based working	1 (commuting travel only)	Unclear	The existence of ICT has increased commuting distance by 13% for each worker between 1996 and 2010.	Average
13	Helminen, V. & Ristimäki, M. (2007)	Finland	Analysis of survey data	Commuting distance reduced by teleworking	1 (commuting travel only)	Reduce	Teleworkers in the survey commute 3.7km further than non-teleworkers. But the use of teleworking (at least once a week) by 4.7% of the Finnish labour force reduces total commuting distance travelled in Finland by 0.7%.	Good
14	Henderson et al. (1996)	USA	Evaluation of teleworking pilots	Commuting distance and emissions reduced by cutting down on need for daily commutes.	2 (commuting travel, non-commuting travel)	Reduce	On non-teleworking days, telecentre-based teleworkers have 91% higher VMT than non-teleworkers, while home-based teleworkers have 54% higher VMT – suggesting they live further from work than regular commuters. On teleworking days, home-based teleworkers have 67% less travel distance than commuters and telecentre workers have 54% less distance.	Average
15	Hjørthol, R. J. (2006)	Norway	Analysis of survey data	Commuting distance reduced by cutting down on need for daily commutes.	1 (commuting travel only)	Reduce	Home-based teleworkers have 'work travel totals by car' that are 8% lower per month than non-teleworkers.	Poor
16	Jaff, M. M. & Hamsa, A. A. K. (2018)	Malaysia	Scenario modelling	Commuting distance avoided by cutting down on need for daily commutes.	1 (commuting travel only)	Reduce	Based on sample, if 2% of female workforce teleworked three times per week, peak-hour traffic could be reduced by 1.3-7.8%. If 2% of female workforce teleworked once per week, peak-hour traffic could be reduced by 0.6%-3.7%	Poor
17	Kim et al. (2015)	South Korea	Analysis of survey data	Distance travelled avoided by the head of house teleworking	2 (commuting travel, non-commuting travel)	Increase	For dual- or multiple-earner households, the household has lower commute travel for the teleworking head (compared to households without a teleworking head), but greater amounts of the other four types of travel (teleworker's non-work travel and other household members' work and non-work travel). As a result, the vehicle miles reduced by the head of household teleworking (-7.8km per day) is offset by the teleworkers' non-commute trips (+24.2km), non-work trips (+11.7km), as well as by other household members' non-work trips (+1.5km). This is because the car (of which there are only 0.91 per household in South Korea compared to 1.79 in the USA) gets used more by other members for other purposes.	Good
18	Kitou, E. & Horvath, A. (2003)	USA	Scenario modelling	Emissions reduced through telework.	3 (commuting travel and office and home energy use)	Unclear.	Teleworking between one, three, and five times a week decreases CO ₂ emissions by between 2-80% (rounded).	Good
19	Koenig et al. (1996)	USA	Evaluation of teleworking pilots	Commuting distance and emissions reduced by cutting down need for daily commutes.	2 (commuting travel, non-commuting travel)	Reduce	Teleworkers had an overall daily travel of 10.2 miles on teleworking days compared with 32.7 miles for non-teleworkers. While non-commute trips increased by 1 per day for teleworkers, their non-commute travel on teleworking days reduced by 0.7 miles, from 34.6 miles per day to 33.9 miles per day. On non-teleworking days, travel distance for teleworkers was 36.9 miles per day, slightly higher than for non-teleworkers (around 32 miles per day), suggesting that teleworkers live further away from work than regular commuters.	Good
20	Lachapelle et al. (2018)	Canada	Analysis of survey data	Travel time reduced by working from home.	1 (commuting travel only)	Neutral	Full time teleworking reduces daily travel time by 13 minutes. Morning peak trips were not avoided because of school runs. Part-day teleworking has no effect on overall travel.	Average

21	Lari, A. (2012)	USA	Analysis of survey data	Travel distance avoided through teleworking.	1 (commuting travel only)	Reduce	On teleworking days, vehicle miles travelled per person was 27.96 miles lower than on a traditional commuting day. Overall, 7.46 million vehicle miles travelled per year were avoided by teleworking among 678 teleworkers. Assuming 1.10 lbs/CO ₂ per mile travelled, eWorkPlace participants saved 4,070 tons of CO ₂ .	Poor
22	Larson, W. & Zhao, W. (2017)	USA	Scenario modelling	Commuting distance and emissions reduced by cutting down on need for daily commutes.	2 (commuting travel and home energy use))	Unclear	If 20% of workers telework one day a week, commuting energy consumption would decrease by 20%, but home energy consumption would increase by 5.3%. Overall energy consumption from the household would increase by 0.4%.	Poor
23	Mamdoohi, A. R. & Ardehshiri, A. (2011)	Iran	Scenario modelling	Peak hour commuting trips avoided through teleworking by 36% of government employees	1 (commuting travel only)	Reduce	If 36% of the 148,551 government employees teleworked once a week, 53,898 peak hour trips could be avoided.	Poor
24	Martens, M. J. & Korver, W. (2000)	Netherlands	Scenario modelling	Commuting trips avoided by teleworking.	1 (commuting travel only)	Reduce	Between 71,000 and 529,000 daily commuting trips could be substituted in the Netherlands through teleworking assuming teleworking rates of 20% and 60%, respectively. This equals a maximum of 5% reduction in commuting travel, and 1% reduction in overall travel.	Poor
25	Matthews, H. S. & Williams, E. (2005)	USA, Japan	Scenario modelling	Net energy savings from teleworking (due to avoided transportation energy use and net building energy consumption)	3 (commuting travel, home and office energy use)	Neutral	For current estimated teleworking populations and practices in the US (currently 0.4% of total worker days, once a week) and Japan (currently 2.5m workers, once a week), there are national level energy savings of only 0.01–0.4% in the US and 0.03–0.36% in Japan. Where 50% of information workers telework 4 days per week, United States and Japan national energy savings are estimated at only about 1% in both cases.	Good
26	Mitomo, H. & Jitsuzumi, T. (1999)	Japan	Scenario modelling	Reduction in peak time congestion	1 (commuting travel only)	Reduce	If 9-14 million workers telework daily, the congestion rate during peak hours will be reduced by 18%-28%.	Poor
27	Mokhtarian et al. (2004)	USA	Evaluation of teleworking pilots	Commuting distance displaced by telecommuting.	2 (commuting travel, non-commuting travel)	Reduce	Average quarterly per capita total commute distances are generally 15% lower for teleworkers than for non-teleworkers, indicating that they telework often enough to more than compensate for their longer one-way commutes (which tend to be on average 16 miles compared with 11 miles for non-teleworkers).	Good
28	Mokhtarian, P. L. & Varma, K. V. (1998)	USA	Evaluation of teleworking pilots	Commuting travel and travel-related emissions avoided through telecentre-based teleworking	2 (commuting travel, non-commuting travel)	Reduce	On teleworking days, distance travelled by centre-based teleworkers decreased significantly compared with regular commuters, by 51 person-miles (58%) and 35 vehicle-miles (53%). There were no increases in non-work travel on teleworking days. When weighted by teleworking frequency (which was just over one time a week for the sample), there were average reductions in total person miles travelled (PMT) of 11.9% and in VMT of 11.5% over a week compared with non-teleworkers.	Good
29	Nelson et al. (2007)	USA	Evaluation of teleworking pilots	Emissions avoided through teleworking programme.	1 (commuting travel only)	Unclear	Impossible to derive meaningful estimates.	Poor
30	O'Keefe et al. (2016)	Ireland	Analysis of survey data	The reduction in emissions through travel-savings via teleworking.	2 (commuting travel, non-commuting travel)	Reduce	Based on patterns in the sample data (which showed that 44% of the population in the Greater Dublin Area teleworks once a month and which showed how certain segments travel to work), teleworking by between 20% and 50% of the population once a week would contribute to emissions reductions of between 31,000 tonnes and 78,000 tonnes of CO ₂ per year.	Good
31	Pratt, J. H. & Trb. (2002)	USA	Analysis of survey data	Daily travel distance avoided through teleworking	1 (commuting travel only)	Reduce	Individuals who part-time telework travel 3.6 miles (or 17%) less on teleworking days for work-related travel than employer-based workers.	Poor

32	Röder, D. & Nagel, K. (2014)	Germany	Analysis of survey data	Potential reduction in energy demand through teleworking.	3 (commuting travel, home and office energy use)	Neutral	Teleworking by 10% of the sample (unspecified frequency) within this model reduces commuter mileage and transport energy consumption by 10% but increases energy consumed at home by about the same amount. By contrast, office energy consumption is barely affected.	Average
33	Roth et al. (2008)	USA	Scenario modelling (based on assumptions drawn from Henderson et al. (1996))	Avoided energy consumption, emissions, and gasoline consumption through teleworking.	3 (commuting travel and office and home energy use)	Reduce	Teleworking by 4 million US workers (3% of the total workforce) one or more days per week could reduce annual primary energy consumption by between 0.13% and 0.18% and CO ₂ emissions by between 0.16% to 0.23%. It could also decrease US light-duty vehicle gasoline consumption by 0.8%.	Average
34	Shabanpour et al. (2018)	USA	Scenario modelling	Avoided commuting distance travelled and emissions from teleworking.	2 (commuting travel, non-commuting travel)	Reduce	When 50% of workers have 'flexible working schedules', total daily VMT and vehicle hours travelled (VHT) can be reduced by up to 0.69% and 2.09%, respectively. Considering the same comparison settings, this policy has the potential to reduce greenhouse gas emissions by up to 0.71%.	Average
35	Shimoda et al. (2007)	Japan	Scenario modelling	Reduced energy consumption from the reduction in commercial energy consumption outweighing increases in residential energy consumption.	2 (home and office energy consumption)	Reduce	Provided the floor area of office buildings being utilized decreases as the rate of teleworking increases, 60% of the population could teleworking lead energy consumption to decrease by 0.6% of the total energy consumption of the residential and non-residential sectors in Osaka City.	Average
36	Van Lier et al. (2014)	Belgium	Analysis of survey data	Commuting distance displaced by teleworking.	1 (commuting travel only)	Reduce	Difficult to say. All that is reported is that working from home reduces teleworkers' commute by 45 km per day on teleworking days and that working in a satellite centre reduces the commute for these workers by 38 km, from 60 km to 22 km per day.	Poor
37	Vu, S.T. & Vandebona, U. (2007)	Australia	Scenario modelling	Car distance travelled avoided by teleworking.	1 (commuting travel only)	Reduce	Assuming a 60 km commute, a once-a-week teleworking frequency by 18% of all workers in New South Wales, and a rate of single-occupier driving of 70%, 3 million vehicle-km (4.2% of the total) could be avoided by 2001 and there could be a reduction of 15.5% of the total by 2021.	Average
38	Williams, E. D. (2003)	Japan	Scenario modelling	Overall energy reduced by teleworking, taking into account changes in travel behaviour and office and home energy consumption (heating and cooling)	3 (commuting travel and office and home energy use)	Reduce	The adoption of 4-day per week teleworking by mobile sales and specialist/technical workforce (approx. 14% of the total workforce) could reduce national energy consumption by 1.0%. If clerical workers (and additional 23% of the workforce) also telework an additional 1.1% of savings become possible.	Poor
39	Zhu, P. Y. (2012)	USA	Analysis of survey data	Whether teleworking reduces overall distance travelled (both work and non-work together) or whether teleworking is a complement to other forms of travel.	2 (commuting travel, non-commuting travel)	Increase	In 2001, teleworkers' work trips were 34.2% longer in distance than non-teleworkers (39 km instead of 29 km); their non-work trips were 17.1% longer (39km instead of 33km). Teleworkers also take more non-work trips than non-teleworkers, 4.39 per day instead of 3.87 per day. In 2009, teleworkers' work trips were 43.3% longer in distance than non-teleworkers, 43 km instead of 30 km; their non-work trips were 15.7% longer, 36km instead of 32 km. Teleworkers frequency of non-work trips had however fallen compared with non- teleworkers, 4.18 per day instead of 3.77 per day. Overall, if the rate of teleworking is 3%, the impact on the monthly round-trip commute distance is negligible.	Good

5. Discussion: Impacts and rebounds of teleworking

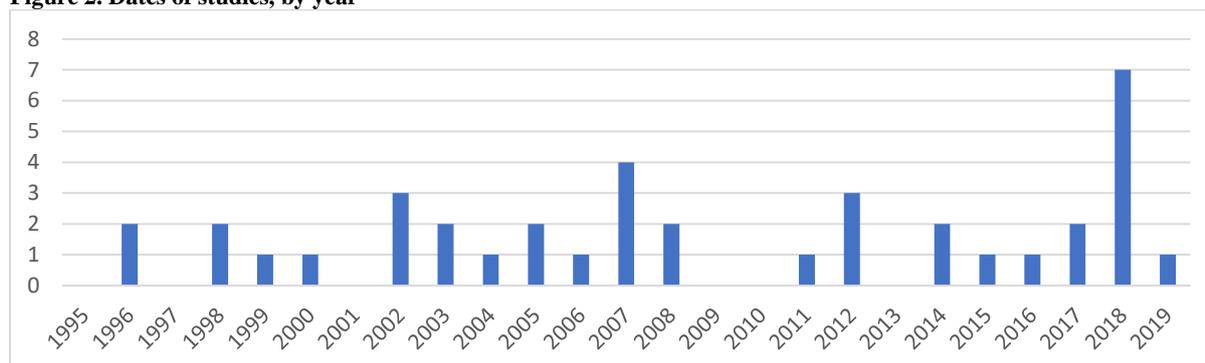
This section discusses the results of the systematic review that are presented in Table 4 and in more in Supplementary Material 2. It first provides an overview of the results, before discussing the sources and conditions of impacts on the relevant metrics, the potential rebound effects from teleworking, the scope of the studies and the methodological quality of the evidence base.

5.1 Overview of the studies

The 39 studies in the final sample examine a range of configurations and scales of teleworking in a variety of contexts. The studies examined two main *types* of teleworking, home-based (35 studies) and telecentre-based (4 studies). As Table 4 shows, most studies are from the US (19 studies) and Europe (11 studies), with only three from the Global South (Thailand, Malaysia, and Iran). The dominance of US studies may influence the overall findings, since most US commuters travel by private car rather than public transport, and vehicles and buildings in the US tend to be larger and less energy efficient than those in other OECD countries.

As Figure 2 indicates, there is a fairly even distribution of studies across the time range (1995 to 2019). While this suggests there has been no slackening of interest in teleworking over this period, the character of teleworking has changed as ICTs have evolved. In particular, telecentre-based teleworking is now largely obsolete, and the three studies that involved the collection of data on telecentre pilot schemes were all published before 1998.

Figure 2. Dates of studies, by year



The studies employ a variety of methods that are described in detail in Supplementary Material 2. The studies also vary in methodological quality and include both *ex post* estimates and *ex ante* projections of impacts on a number of different metrics (e.g. commuting trips, commuting distance, energy consumption). These methods can be grouped into three broad categories:

Scenario modelling: using simulation models or other types of model to project future impacts from teleworking (often using rather sparse datasets) (e.g. Larson & Zhao 2017).

Quantitative analysis of survey data: using publicly available datasets on transport and working behaviour, often from national surveys, to estimate the historical impacts of teleworking on energy use and other indicators (e.g. Chakrabarti 2018).

Evaluation of teleworking pilots: using ‘travel diary’ data to establish travel patterns and energy use among teleworkers and non-teleworkers (e.g. Balepur et al. 1998).

Table 5 summarises the primary method used, with the specific studies referenced to the list in Table 4².

Table 5. Classifying studies by method

Type of method employed	No. of studies using this method	Specific studies using this method
Scenario modelling	14	4, 8, 16, 18, 22, 23, 24, 25, 26, 33, 34, 35, 37, 38
Analysis of survey data	19	1, 2, 5, 6, 7, 9, 10, 11, 12, 13, 15, 17, 20, 21, 30, 31, 32, 36, 39
Evaluation of teleworking pilots	6	3, 14, 19, 27, 28, 29

Table 6 classifies the studies by their *scope*, or the ‘number of impact categories’ included. We distinguish four categories of impact, namely the energy used in: a) commuting; b) non-work travel; c) the home; and d) the office. Most studies do not estimate energy consumption directly, but use other metrics (such as ‘distance travelled’) that serve as proxies for energy consumption. While there may be additional impact categories, such as economy-wide rebound effects, these are not included in any of the reviewed studies. The scope of a study depends in part upon the research questions employed: for example, if the primary interest is the impact of teleworking on congestion, a narrow scope is appropriate. Conversely, if the primary interest is the impact on energy consumption, a wide scope is appropriate. While our interest lies with the latter, studies with a narrow scope nevertheless provide useful evidence on the impacts on energy consumption within a particular area.

While approximately half the studies (nineteen) only consider the impact of teleworking on commuter travel, the remainder estimate a wider range of impacts. For example: twelve studies *also* estimate the impact on non-commuting travel by either the commuter or other household members; five studies estimate the impacts on home and/or office energy use as well as commuting travel; and two studies estimate the impacts on commuting travel and home energy use (but not on non-work travel). An exception is Shimoda et al. (2007), who ignore the impact on travel altogether and only consider the impact on home and office energy consumption. It is notable, however, that *none* of these studies encompass all four of our impact categories.

Table 6. Classifying studies by scope

Scope of studies (impact categories included)				No. of studies with this scope	Studies with this scope
Commuting travel	Non-work travel	Home energy use	Office energy use		
X				19	1, 2, 4, 6, 8, 11, 12, 13, 15, 16, 20, 21, 23, 24, 26, 29, 31, 36, 37,
X	X			12	3, 5, 7, 9, 14, 17, 19, 27, 28, 30, 34, 39
X		X		2	10, 22
		X	X	1	35
X		X	X	5	18, 25, 32, 33, 38

Table 7 summarises our assessment of the methodological quality of each study. We ranked 14 of the studies as methodologically ‘good’, 11 as ‘average’ and 14 as ‘poor’. Some justification for these rankings can be found in Supplementary Material 2. Section 5.5 discusses the relevance of methodological quality to the estimated impacts on energy consumption.

² Note that some studies used more than one method. For example, some studies based primarily on survey data *also* utilize some secondary transport data to establish teleworking impacts.

Table 7. Classifying studies by methodological quality

Methodological quality	No. of studies of this standard	Specific studies of this standard
Good	15	3, 5, 6, 7, 9, 10, 13, 17, 18, 19, 25, 27, 28, 30, 39
Average	10	2, 11, 12, 14, 20, 32, 33, 34, 35, 37
Poor	14	1, 4, 8, 15, 16, 21, 22, 23, 24, 26, 29, 31, 36, 38

5.2 A summary of the energy, climate and environmental impacts of teleworking

Table 8 shows that the majority of the studies (26 out of 39) suggest that teleworking (both from home and telecentres) leads to a net *reduction* in energy use and/or emissions, with only five studies finding a net increase. These benefits largely result from the elimination of the commute, reductions in congestion, concomitant reductions in vehicle emissions, and reductions in office-based energy consumption.

Table 8. A summary of the net impacts of teleworking on energy across the final sample of studies

Impact of teleworking	Reduce	Neutral	Increase	Unclear
No. of studies	26	3	5	5

While most studies compare the *net* energy/environmental impacts of a teleworking and non-teleworking mode of working, a few studies (e.g. Atkyns et al. (2002)) provide only *absolute* estimates of changes in key variables, such as gallons of gasoline saved. These studies are less useful than those providing relative figures expressed in terms of a percentage gain or loss. Only the latter are included in Table 9, which displays the full range of estimates found in our sample of the net impact of teleworking on different metrics. As with scope, the diversity of metrics used by the different studies reflects their different research questions.

While all of the metrics in Table 9 are relevant to the impact of teleworking on energy consumption (our research question), some are more useful than others. It is important to stress, furthermore, that the estimations in Table 9 are a mix of relative and absolute figures, reflecting the diversity of the studies. So, while some studies estimate the energy savings from telecommuting versus not telecommuting for single journeys (a *relative* figure), other studies estimate the *total* energy savings based on a specific proportion of the population telecommuting a certain number of times per week or month (an *absolute* figure). This multiplicity of different study contexts therefore makes it difficult to normalize results across studies in order to compare estimates of energy savings.

Table 9 indicates that the most commonly used metric (used by 26 of the 39 studies) is ‘vehicle distance travelled’, which is a proxy for the energy consumed by motorized travel (invariably commuting-related travel). Studies using this indicator give the widest range of estimates, ranging from a 20% reduction in distance travelled (Balepur et al., 1998), to a 3.9% increase (De Abreu e Silva & Melo, 2018). These studies either measure or assume different *proportions* of teleworkers and/or differing *frequencies* of telework, making comparison between them difficult. In addition, most of the studies do not disaggregate ‘avoided travel’ by mode and instead (implicitly) assume that it relates to travel by private car. In fact, De Abreu e Silva & Melo (2018) is the only study to recognise that the (avoided) commuter travel may be by other modes such as public transport. This bias partly reflects the dominance of US studies, but the assumption that avoided travel *necessarily* take the form of avoided car travel may lead to an overestimate of energy savings (see Section 5.6).

While many studies estimate the impacts of teleworking on weekly distance travelled, they typically confine attention to commuter travel and hence neglect non-work travel. As a result, they may

overestimate the total reduction in travel distance. For example, Hjorthol (2006), who only considers work travel by car, finds that vehicle travel distance is 8% lower per month for teleworkers than non-teleworkers; whereas Zhu (2012), who *also* considers impacts on non-work travel, finds a negligible impact on total vehicle distance travelled. This pattern is visible across the studies, with studies with a wider scope (i.e. including more impact categories) tending to provide lower estimates of energy or travel savings. This point is discussed further in Section 5.6.

Six of the studies measure the impact on ‘person distance travelled’, rather than vehicle distance travelled, and find that teleworking reduces the former by between 11.9% and 19%. This is less useful, however, since it does not tell us *how* the commuter was travelling (e.g. by car or public transport), or whether they were sharing the vehicle with other occupants. For example, ‘person distance travelled’ could increase owing to a longer commute, while ‘vehicle distance travelled’ could fall owing to greater use of public transport – and the latter is more strongly correlated with energy consumption (Henderson et al. 1996).

Seven studies measure impacts in terms of the *number* of commute trips and find reductions of between 2.3% and 30% per week. This metric tells us less about energy savings however as it does not indicate the distance travelled. Mitomo and Jitsuzumi (1999) measure impacts in terms of time savings from reduced traffic congestion and estimate that these range from 1.9% to 28%, with implications for energy use and emissions from stationary traffic.

Seven studies estimate the impact of teleworking on energy consumption and estimate reductions of between 0.01% and 14%. Several of these take into account the impacts on both commuting energy use and home or office energy. For example, Matthews and Williams (2005) estimate that, if half of the ‘information workers’ in the US and Japan telework four days per week, this would reduce primary energy consumption by ~1%. Finally, ten studies suggest that teleworking could reduce carbon emissions by between 0.1% and 80%, with this higher estimate assuming a 5-day teleworking routine by the whole population (Kitou & Horvath 2003).

Table 9. The range of estimated impacts of teleworking on different metrics within the final sample of studies

Metric	Measures	No. of studies using this metric ³	Range of net impacts ⁴
Vehicle distance travelled	Miles, km	26	-20% to +3.9%
Person distance travelled	Miles, km	6	-19% to -11.9%
Commuter trips	No. of trips	7	-30% to -2.3%
Congestion	Minutes in congestion	3	-28% to -1.9%
Overall energy use	MJ, kWh, litres of fuel	7	-15% to -0.01%
CO ₂ emissions	Grams, tonnes	10	-80% to -0.1%

5.3 Sources and estimates of environmental benefits from teleworking

The majority of the 39 studies suggest there are energy savings and other environmental benefits from teleworking. This section examines the main sources and estimates of these savings in more detail and contextualizes these results in terms of the broader literature.

Elimination or reduction of commutes

The main source of energy savings is the reduction in commuter travel to and from work. This is a substitution effect, whereby ICT facilitates remote working and removes the need to commute for at least part of the week. Overall, the studies suggest varying reductions, in weekly, monthly or annual vehicle distance travelled, up to a maximum of 20%. They also suggest corresponding benefits,

³ Some studies examine more than one indicator, so the total in this column sums to more than 39.

⁴ These impacts are under very different conditions and are estimated using very different methodologies. For more detail, see Supplementary Material 3.

including reductions in the number of trips by up to 30%, time savings from reduced congestion of up to 28% (which in turn could lead to significant energy savings since slow-moving traffic is inefficient), and associated reductions in carbon emissions. It should be stressed, however, that the majority of the studies finding reductions in vehicle distance travelled neglect potential rebound effects – such as increased non-work travel (see Section 5.4).

Studies of telecentre workers find significant reductions in commuting distance travelled. For example, Balepur et al. (1998) show how participants in the Puget Sound pilot who teleworked once a week reduced their total weekly commuting vehicle travel by 19% (10 miles). However, different studies make different estimates of, or assumptions for, the number of households that are teleworking and the frequency with which they are teleworking. They also estimate both *relative* and *absolute* figures, making it difficult to compare their estimates of travel/energy savings and to generalise their findings. For example, Choo et al. (2005) estimate that teleworking is practised by 12% of the US workforce once a week and estimate a resulting 0.8% reduction in the total distance travelled by private cars. In contrast, Martens & Korver (2000) assume a teleworking rate of ‘between 20% and 60%’ of the US working population and estimate a resulting 5% reduction in vehicle distance travelled. But Martens and Korver (2000) do not state the assumed *frequency* of teleworking (i.e. how many times per week these 20%-60% of the population will telework). They moreover make arguably unrealistic assumptions about the potential future uptake of teleworking considering that the current proportion of teleworkers is only 9% in the US and 5% in the UK. Other studies (e.g. Röder & Nagel (2014)) fail to state *either* the proportion of the population teleworking *or* their frequency of teleworking, making it impossible to extrapolate useful lessons from their results.

The studies also relate to very different geographical contexts, where differences in the patterns and modes of commuting differ have important implications for the potential energy savings from teleworking. For example, Helminen and Ristimäki (2007) estimate that teleworking by 4.7% of the Finnish labour force once a week would reduce commuting distance travelled by 0.7%. Larson and Zhao (2017) meanwhile estimate that if 20% of US workers telework once a week, commuting energy consumption would decrease by 20%. However, Finland and the US differ significantly in terms of the average distance between home and work, the modal mix for commuter travel and the relative energy efficiency of different modes; with the result that the energy savings from teleworking in Finland may be substantially lower than in the US. For example, while Helminen and Ristimäki (2007) state that 70% of the Finnish population commute by car or motorbike, Larson and Zhao (2017) assume that all US commuting is by car. This means that the energy savings from telecommuting will be higher in the US, where the forgone travel is in the form of avoided car trips, compared with Europe, where a large proportion of commuting is by other modes (Van Lier 2014).

For our purposes, however, the most fundamental problem with many of the studies is their limited *scope*. Indeed, whether teleworking reduces economy-wide energy consumption depends upon the impacts on commuting travel, non-work travel, home energy use and office energy use, together with the relative energy efficiency of transport modes, homes and office buildings. Most studies only provide a partial coverage of these different variables. While some studies examining both work and non-work travel find that increases in non-work travel as a result of teleworking do *not* lead to increases in overall travel (e.g. Mokhtarian & Varma 1998), others find evidence to the contrary (e.g. Zhu 2012). Capturing these nuances in order to appraise the impact of teleworking on *overall* energy use is difficult but essential – an issue that will be returned to in Section 5.5.

Reductions in office energy consumption

Some of the literature on ICT and energy suggests that more remote working may lead to higher energy consumption at home (e.g. Chapman 2007). However, several studies show how, even

allowing for increases in home energy consumption, teleworking could achieve overall energy savings since it enables reductions in per capita office space (e.g. through hot-desking) and potentially means that offices no longer need to be heated or cooled to the same level or for the same period of time. Williams (2003), for example, estimates that the adoption of 4-day per week teleworking by the specialist/technical workforce in Japan (~14% of the total) could reduce national energy consumption by 1.0% by eliminating the need for office heating and cooling on non-working days. Similarly, Matthews and Williams (2005) estimate that the potential energy savings from reducing office space are comparable to those from reduced commuting. In countries such as Japan, where there is a lower level of office space per worker, the energy savings from reduced office use may be smaller than in the USA, where offices tend to be larger (Matthews and Williams 2004). The gains may also be smaller in more temperate regions, since less energy is required to heat and cool office buildings (Kitou & Horvath 2003) and may also be partly offset by the embodied energy associated with duplicated equipment such as printers. The latter forms part of the direct impacts of ICT on energy consumption (Table 1), but this is ignored in all of the reviewed studies.

As with gains from reduced commuting, these potential gains also depend upon a range of factors, including the extent to which firms downsize or close their offices as the number of teleworkers increase. Shimoda et al. (2007) estimate that, if utilised office space decreases in proportion to the rate of teleworking, full-time teleworking by 60% of workers in Osaka City (Japan) would reduce total energy consumption for residential and non-residential buildings by 0.6%. Shimoda et al. (2007) stress, however, that if teleworkers are only part-time, companies may not down-size their offices or reduce energy consumption since they will need to retain the same sized offices for the days that teleworkers join non-teleworkers in the office. Since part-time teleworking is more common than full time teleworking, the latter appears a more likely outcome. Thus, the potential gains in terms of reduced office energy consumption may not be realised.

More generally, Shimoda et al. (2007) demonstrate that, even assuming office energy use falls in proportion to the rate of teleworking, very high levels of teleworking may achieve only modest reductions in aggregate energy consumption. Similar conclusions are reached by Matthews and Williams (2005), who estimate that if all US 'information workers' teleworked four days a week, US energy consumption would fall by only ~2%. This is partly because teleworking is expected to be suitable for less than half of the US workforce. For comparison, Matthews and Williams (2005) estimate that a 20% improvement in average car fuel efficiency in the US would reduce aggregate energy use by ~5.4%.⁵

Although Shimoda et al. (2007) provide some useful evidence about the potential impacts of teleworking on home and office energy consumption, their study provides no analysis of the impacts of teleworking on work or non-work travel. Hence, it still provides only a partial picture of the net impacts of teleworking on energy consumption.

5.4 Rebound effects from teleworking

While teleworking is framed by some studies as a promising way to reduce energy consumption, particularly from commuting travel, other studies draw attention to potential unintended impacts that could increase energy consumption and negatively affect various environmental indicators. They also highlight the uncertainty about the impacts of teleworking, owing to the complexity of impact pathways and the unpredictability of human behaviour.

⁵ The proportional reduction in emissions contributing to poor air quality may be larger, since these are particularly concentrated in the road transport sector.

Dispersion of residential location and longer commutes

Although 70% of the studies in our review suggest that teleworking reduces energy use, five studies – which we also consider to be methodologically rigorous – suggest that the gains from eliminating commutes on teleworking days may partly or wholly offset by longer commutes on non-teleworking days (Balepur et al. 1998; Chakrabarti 2018). For example, Helminen and Ristimäki (2007) find that Finnish teleworkers have a 3.7 km longer commute than non-teleworkers. This concurs with De Abreu e Silva & Melo's (2017) finding that, controlling for a wide range of sociodemographic variables, UK teleworkers (in one-worker households) have a 10.7 mile longer commute than non-teleworkers. Several studies moreover find that some teleworkers also travel further than regular commuters on days that they are *not* teleworking. For example, Henderson et al. (1996) find that home-based teleworkers in the US travel 67% less than regular commuters on teleworking days, but 54% *more* on non-teleworking days. Thus, over the course of a week – and given a part-week teleworking lifestyle – teleworkers may potentially travel further than regular commuters.

However, such studies do not establish the direction of causality, i.e. do people telework to avoid a long commute (and/or a slow or difficult commute), or do they *choose* to live further away from the workplace because their job *enables* them to telework? One approach to identifying whether teleworking has a causal influence on commuting distance is to use instrumental variables. In his analysis of US national household survey data, Zhu (2012) used the frequency of internet use as an instrument for teleworking since this should be correlated with the latter while not affecting commuting distance. Zhu (2012) finds that teleworking has a positive influence on commuting distance that has increased over time. In 2009, US teleworkers' work trips were 43% longer in distance than those of non-teleworkers – compared to 34% in 2001.

An alternative approach to addressing endogeneity is to use panel data, since this allows the changes in teleworking and commuting distance over time to be identified whilst controlling for time-invariant fixed effects. Using this approach, de Vos et al. (2018) estimate that Dutch teleworkers have 5% longer commuting times on average, with every additional day of home working being associated with a 3.5% longer duration commute. In a more recent study using a different data set, de Vos et al. (2019) obtain larger estimates of 12% and 16% respectively. Both studies use commuting duration rather than commuting distance as the dependent variable, but these two variables should be correlated – and Zhu's (2012) results suggests that the impact of teleworking on distance travelled could be larger than the impact on commuting duration.

Overall, evidence from both the US and Europe suggests that the adoption of teleworking may induce long-term changes in residential location that offset some of the environmental benefits. The size of this effect may be expected to vary with contextual factors, such as the differential in property prices between urban and peri-urban regions and the financial and temporal cost of the commuting journey. However, it seems clear that, in some circumstances, the increased adoption of part-time teleworking could *increase* weekly, monthly, or annual commuter travel. More generally, the environmental benefits of teleworking will depend upon both the frequency of teleworking and how far teleworkers live from their workplace (Lachapelle et al. 2018).

Non-work travel

Another potential unintended effect of teleworking is that it may encourage more non-work travel. In this case, the travel avoided by the daily commute is partly or wholly offset by additional travel by the teleworker for other reasons. This is sometimes termed a 'complementary' effect of teleworking (Mokhtarian 2002, 2009). Several studies find such effects, though it is important to underline that they only do so because their wider scope enables the interactions between teleworking behaviour and non-work travel to be explored.

For example, Ellder (2017) finds that teleworkers travel further than non-teleworkers on *both* teleworking *and* non-teleworking days. While non-teleworkers travelled an average of 46 km per day, teleworkers travelled 54 km on teleworking days and 64 km on non-teleworking days. Similarly, Zhu (2012) find that, according to US National Household Travel Surveys (NHTS), teleworkers took 10.8% more non-work trips per day than non-teleworkers (4.18 versus 3.77) and that these were, on average, 15.7% longer (36 km versus 32 km). Again, using instrumental variables, Zhu (2012) finds that teleworking has a significant impact on non-work travel.

The reasons for greater non-work travel on teleworking days are complex and are not explored by most of the studies in the sample. Of the studies that did attempt to explain causality, Zhu (2012) suggests that non-commuting workers are less able to ‘daisy chain’ (or ‘link’) trips together in an efficient way, and thus have to make specific trips for non-work activities. This effect may be particularly pronounced where there is one household member who works: with that member no longer commuting, other household members may have to make separate trips out to carry out specific non-work duties (Kim et al. 2015; De Abreu e Silva & Melo 2018). The distance travelled for non-work activities will also vary with geographical context, including the proximity of the home to schools, retail outlets and other destinations - which again suggests that the results from US studies may not necessarily apply to other contexts.

Teleworking could also increase daily/weekly travel among those who telework by creating a displacement effect, whereby commuting trips are replaced with other forms of non-work travel, such as leisure trips (Lachapelle et al. 2018). These trips could be due to boredom or could merely be opportunistic where teleworkers take advantage of their free time to travel more or to engage in more social activities (Rietveld 2011). This type of induced travel is consistent with the broader evidence on the stability of daily travel time in widely different contexts – at slightly over one hour a day (Schäfer & Victor 1997; Stopher et al. 2017).

The evidence for a definitive, non-work travel rebound is, however, inconclusive. For example, Mokhtarian and Varma (1998), in their analysis of travel diary data in a teleworking pilot in California, find no evidence of increased non-work travel on teleworking days. However, this lack of evidence is partly because most studies neglect non-work travel altogether, and therefore fail to detect these effects. For example, although only 15 of the 39 studies in our sample examine non-work travel, five of these find complementary travel effects. As most studies focus more narrowly upon commuter travel and ignore interactions between teleworking practices and non-work travel, it seems likely that they overestimate the energy savings from teleworking.

Intra-household dynamics and non-work travel

The potential rebound effects discussed above may be further amplified by intra-household travel dynamics. Indeed, two studies examined the ways in which the travel behaviour of all household members is affected by one or more members’ teleworking. De Abreu e Silva and Melo (2018), for example, find that the travel effects of teleworking by one household member were different when there were two household members working. Using UK National Travel Survey data, they find that higher teleworking frequencies in one-worker households were associated with more travel by all modes, particularly by car. But in two-worker households, the estimated increase in travel was much smaller and not statistically significant. They claim that this lower increase in travel in two-worker households is due to a greater degree of sharing of household-related travel tasks between workers.

In South Korea, an additional effect was discovered, whereby home-based working by the ‘head of household’ led the level of household vehicle usage to increase. Using cross-sectional data for Seoul, South Korea, Kim et al. (2015) find that teleworkers’ non-work trips as well as his/her household

members' non-work trips were greater than those of non-teleworkers and their household members. While the daily distance travelled by the teleworking head of household fell by 7.8 km per day, this was offset by increases in the teleworker's non-commute travel (+24.2 km per day), as well as by increased non-work travel by other household members' (+1.5 km per day). But these differences were only significant in households with less than one vehicle per employed member. Car ownership is lower in South Korea than the USA (0.91 per household compared to 1.79), so the car is more of a scarce commodity. More generally, the focus of the teleworking literature on the US (where per capita car ownership is exceptionally high) may have led researchers to pay insufficient attention to the induced impact on travel by other household members.

5.5 Reflections on the types of teleworking and teleworkers

The studies examined two types of teleworking: home-based and telecentre-based. It is however difficult to assess the merits of one type over the other due to the highly specific conditions examined by different studies.

In terms of *types* of teleworkers, most studies examined office-based and computer-dependent workers, recognizing that these professions have the greatest potential for teleworking. For example, Williams (2005) estimated that approximately 40% of jobs in the US and Japan would be suitable for teleworking. Within this group, studies emphasise that, above all, it is the frequency of teleworking over the course of a week that is the crucial factor in determining impacts – especially among those who live far from their place of work. Thus, from this perspective, it is full-time (or near full-time) telework that has the greatest potential for energy savings. Many of the studies examine schemes within larger companies (e.g. Atkyns et al. 2002) and suggest that mass teleworking may be more realistic within large firms that can still retain a few office-based workers. In contrast, small firms whose workers take on multiple roles may be less able to encourage teleworking (Aguilera et al. 2016).

While most studies investigate the impacts of a single teleworker, others examine the impacts of intra-household travel dynamics where more than one household member works, suggesting that teleworking impacts may be conditional on households being able to *reconfigure* non-work duties (e.g. De Abreu e Silva & Melo 2018). This would depend on economic and social capacity, as daily commuting may be an important part of households' economic strategy, with commuting travel being combined with other non-work duties, such as childcare and shopping.

Beyond the fairly unsophisticated analysis of the differing temporal frequencies of teleworking and certain intra-household work and travel dynamics, there is relatively little exploration of social differentiation among teleworkers and its impact on energy, suggesting that further research would be useful in this area. For example, none of the studies examine the gender dimensions of teleworking, although some studies in the *preliminary* sample of studies (e.g. Jaff & Hamsa 2018) consider such dynamics. Nor do any of the final studies examine other demographic dimensions of teleworking, such as ethnicity or political affiliation. However, many studies note the importance of household income, and observe that wealthier households may have longer commute distances on non-teleworking days (e.g. Fu et al. 2014; Kim et al. 2015).

5.6 Methodological assessment: a question of robustness and scope

As noted, the studies vary widely in both methodological quality and scope – raising the question of whether there is any correlation between these variables and the estimated impacts of teleworking. Table 10 maps our assessment of methodological quality against the sign of the estimated impact. This suggests that the more methodologically rigorous studies are *less likely* to estimate energy

savings from teleworking. Specifically, 19 out of the 27 studies judged to be methodologically ‘poor’ or ‘average’ found reductions in energy use, while all six of the studies that found that teleworking led to negligible reductions or an increase in energy use were judged to be methodologically ‘good’.

Table 10. Methodological quality of studies mapped against the impacts of teleworking

Methodological quality of study	Study assessment of impact of teleworking impact on energy				
	Reduction	Neutral	Increase	Unclear	Total
Good	7	1	5	1	14
Average	8	2	-	1	11
Poor	11	-	-	3	14
Total	26	3	5	5	39

In terms of methods, Table 11 shows that the strongest studies tended to be those analysing survey data, especially those using large-scale national transport surveys and using panel and time-series data on work and travel behaviour (e.g. Kim et al. 2015; Chakrabarti 2018). Although based on much smaller data sets, the studies examining specific teleworking pilot schemes – either within firms or within bounded regions (e.g., Henderson et al. 1996) – also contain rich data on travel behaviour in response to teleworking. The weaker studies meanwhile projected future impacts from teleworking using scenario modelling rather than estimating historical impacts. These studies frequently relied upon limited datasets and/or unrealistic assumptions (e.g. Dissanayake & Morikawa 2008; Mamdoohi & Ardeshiri 2011). More fundamentally, as they are projecting impacts rather than measuring them, those impacts would appear to rely upon modelling assumptions rather than empirical data. They are therefore a much weaker form of evidence.

Table 11. Classifying studies by methodological type and methodological quality (number of studies)

Methodological quality	Scenario modelling	Analysis of survey data	Evaluation of teleworking pilots	Total
Good	2	9	4	15
Average	4	5	1	10
Poor	8	5	1	14
Total	14	19	6	39

Table 12 maps the scope of the studies against the sign of the estimated impacts. This suggests that studies with a wider scope are also more likely to find that teleworking leads to an *increase* in energy use, or else has a negligible impact on energy use. Indeed, Table 11 shows that *all* five of the studies finding that teleworking lead to an increase in energy use examined at least two variables – typically the impact on commuting travel *and* non-commuting travel. By contrast, 15 of the 27 studies finding that teleworking causes a reduction in energy use examined the impact on commuting travel alone.

Table 12. Mapping the scope of studies against the impacts of teleworking

Study scope	Study assessment of teleworking impact on energy consumption				Total
	Reduction	Neutral	Increase	Unclear	
Only the impact on commuting travel	15	1	-	3	19
The impact on commuting travel <i>and</i> one other variable	8	-	5	1	14
The impact on <i>only</i> home and office energy demand (and not travel)	1	-	-	-	1
The impact on commuting travel <i>and</i> two other variables	2	2	-	1	5
Total	26	3	5	5	39

Finally, Table 13 shows the relationship between methodological quality and scope, with the studies having a wider scope (considering impact variables beyond just commuter travel) tending to be judged of higher methodological quality. Conversely, most of the studies with a narrower scope

(considering the impact on commuter travel alone) are judged of lower methodological quality. Specifically, we can see that 17 out of the 19 studies with a narrow scope were rated methodologically poor or average, while 13 out of the 20 studies with a wide scope were rated methodologically good.

Table 13. Mapping the methodological quality and scope of studies against the impacts of teleworking

	Narrow scope (commuter travel alone)	Wide scope (commuter travel and additional variables)
Methodologically average or poor	17	7
Methodologically good	2	13

Overall, this analysis suggests that researchers should be wary of drawing conclusions from methodologically weaker studies that also have a narrow scope.

6. Conclusion and implications

This article has conducted a systematic review of the evidence on the impacts of teleworking on energy consumption. It reduced an initial sample of over 9,000 academic articles to a final sample of 39 relevant studies by using specific inclusion and exclusion criteria. The final sample contained studies which investigated teleworking in a variety of contexts and which employed a range of different research methods – including scenario analysis and the quantitative analyses of survey data. The studies were predominantly focused on the US, with fewer from the EU and only three from the Global South. The studies mainly examined home-based teleworking, with three older studies examining experience with telecentres.

Overall, 26 out of 39 studies found that teleworking reduced energy use via a substitution effect, with only eight studies finding that teleworking led to higher – or else had a negligible impact on – energy use. This suggests that teleworking has some potential to reduce energy consumption and associated emissions – both through reducing commuter travel and displacing office-related energy consumption. However, a major difficulty in establishing whether teleworking does lead to a consistent relative reduction in energy use is the fact that every study provides estimates of energy savings based on a completely different set of conditions. Indeed, while some studies estimate the energy savings from telecommuting versus not telecommuting for single journeys (a *relative* figure), other studies present estimations of the total energy savings based on a specific proportion of the population telecommuting a certain number of times per week or month (an *absolute* figure). Some studies do not moreover even specify the frequency of teleworking (nor the proportion of teleworkers within the population) that their estimates are based on. This makes it difficult to establish an estimate of relative energy savings for a standardized time period. It also demands that researchers examine closely the specific configurations of conditions within particular studies that have led to particular estimates to be made for specific time periods.

While most studies conclude that teleworking can contribute energy savings, the more rigorous studies and/or those with a broader scope present more ambiguous findings. Indeed, where studies include additional impacts, such as non-work travel or office and home energy use, the potential benefits appear more limited – with some studies suggesting that, in the context of growing distances between the workplace and home, part-week teleworking could lead to a net *increase* in energy consumption. In short: it is likely that many studies in the sample may have concluded that teleworking reduces energy use because their scope was too narrow – a problem identified by Mokhtarian (2009, p. 43):

Although direct, short-term studies focusing on a single application (such as teleworking) have often found substitution effects, such studies are likely to miss the more subtle, indirect, and longer-term complementarity effects that are typically observed in more comprehensive analyses.

These uncertainties and complexities suggest that, despite the positive evidence for energy savings that was found across the sample of studies, we should be cautious in drawing conclusions about the scale and consistency of energy savings from teleworking. Context matters, and in many circumstances the savings could be negative or non-existent. Moreover, the associated carbon savings will depend upon additional factors such as the carbon intensity of the energy used for transport (e.g. conventional versus electric vehicles), as well as that used for heating and cooling buildings (Moradi & Vagnoni 2018) (Giovanis 2018). Both of these are undergoing rapid change.

Furthermore, while ‘teleworking’ or ‘telecommuting’, as terms, predate the internet itself, they also arguably refer to practices that do not reflect the dynamic new realities of working practices. Indeed, the technological basis of the working environment has changed dramatically since the 1990s, driven in part by the panoply of new innovations, such as ‘cloud’ storage, ubiquitous high-bandwidth Wi-Fi, video streaming, and ‘5G’ mobile services (Appio et al. 2018). So too has the range of social forms of work, with stable, single-location jobs yielding to ‘zero hours’ contracts and flexi-time arrangements (Akbari & Hopkins 2019). In short, modern modes of flexible or mobile work have become so non-linear and fluid (but also increasingly energy intensive in places) that it has become increasingly difficult to track their energy footprint, or to compare it with a dissolving notion of ‘regular’ work (Hopkins & McKay 2019).

Studies interested in appraising the potential of more flexible, ICT-enabled work practices should therefore aim to combine a range of methods capable of capturing the dynamic new configurations of working conditions. As well as accounting for change in commuting travel, non-commuting travel, distance between home and office, and home and office energy consumption, these studies must also consider other factors, such as the mode of commuting transport in the region being studied and the ways that people choose to use their time when they no longer have to commute to and from work. As many of these realities can only be established through qualitative methods, modellers must work together with other social scientists in order to build a better picture of the changing patterns of work and the energy potential of new forms of socio-technical behaviours (e.g. Hampton 2017).

Finally, as ‘flexible work’ has become increasingly dependent on new energy-intensive forms of digital technologies (not to mention the reliance on rare earth metals and minerals (e.g. Sovacool et al. 2019)), researchers should examine critically whether indeed new, flexible ways of working are indeed ‘sustainable’, in the broadest sense (Mattila et al. 2014; Priest et al. 2016). Future studies in this area should therefore aim to combine a range of methods, types of work, and work arrangements in order to attempt to capture the dynamic configurations of conditions that could potentially support teleworking as a socially, economically, and environmental constructive policy for the future.

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